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# Probing dissociation of space-like photons in deep-inelastic lepton-nucleon scattering

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## Abstract

It is shown that the hadronic dissociation of space-like ( $Q^2 > 0$ ) photons can be directly probed by performing measurements in the fragmentation region of transversely polarized and unpolarized proton beams at the electron-proton collider HERA. Measurements of momentum-distributions in the photon-fragmentation region in normal and in LRG (large rapidity gap) events are also suggested — especially when the scattered proton or neutron in the proton-beam direction is tagged. It is pointed out that such distributions can yield useful information on the mechanisms of hadronic fragmentation in general, and answer the following questions in particular: Is the well-known hypothesis of limiting fragmentation (HFL) valid in color-exchange, in flavor-exchange, or only in vacuum-quantum-number-exchange processes ?

It is known already for a long time that hadronic dissociation of space-like photons may play a significant role in deep-inelastic lepton-hadron scattering — especially in diffractive processes [1,2]. People seem to agree [1-18] that, viewed from the hadron- or nucleus-target, not only real, but also space-like photons ( $Q^2 \equiv -q^2 > 0$ , where  $q$  is the four-momentum of such a photon) may exhibit hadronic structure. But, as far as the following questions are concerned, different theoretical models [1-18] seem to give different answers. How do such hadronic dissociation processes depend on the standard kinematic variables of deep-inelastic lepton-nucleon scattering, namely on  $Q^2$  and on  $x_B \equiv -q^2/(2pq)$ , where  $p$  is the four-momentum of the struck nucleon? In particular, how do such virtual photons behave in the small  $x_B$  and large  $Q^2$  regions where the photons are far from their mass-shells, for example  $x_B = 10^{-2}$  and  $Q^2 \approx 2000 \text{ (GeV/c)}^2$  — values which can be readily reached at HERA? We think it would be useful to answer these questions directly — by performing measurements in deep-inelastic lepton-hadron scattering processes. The reasons are the following:

I. Viewed from the rest frame of the struck nucleon mentioned above, the lifetime  $\tau_\gamma$  of the virtual hadronic system (of quark-antiquark pair or pairs) is of the order  $2\nu/Q^2 = 1/(Mx_B)$ , where  $\nu$  is the photon-energy and  $M$  is the proton-mass. This means, the corresponding longitudinal dimension — also known as the formation/coherence length — of such a virtual state is of the order 100 Fermis for  $x_B = 10^{-2}$ . Furthermore, we note that  $\tau_\gamma$  is a function of  $x_B$ , independent of  $Q^2$ . Does it imply that the hadronic dissociation of a photon always takes place — independent of its virtuality  $Q^2$ ? Is it true that, in high-energy deep-inelastic lepton-hadron scattering processes, we are practically *always* dealing with hadron-hadron collisions, when  $x_B$  is sufficiently small ( $x_B \sim 10^{-2}$ , say)?

II. Some of the dynamical models based on such a photon-dissociation picture (See e.g. Refs.12-18 and the papers cited there) have been used to describe quantitatively the proton structure function  $F_2^p(x_B, Q^2)$  in the small  $x_B$  region and the obtained results are in reasonable agreement with the existing data [19,20]. Can we, on the basis of this agreement, say: “Experiments show that space-like photons  $\gamma^*(Q^2)$  always dissociate into hadronic

systems — independent of their virtualities ( $Q^2$ -values)” ?

III. Until now, besides the measurements of the proton structure function  $F_2^p(x_B, Q^2)$  in the small- $x_B$  region, the only “direct experimental tests” for such pictures and/or scenarios have been deep-inelastic lepton-nucleus scattering experiments (See e.g. Ref. 18), in which information on photon-dissociation can be extracted from the reactions between the space-like photons and (light and heavy) nuclei. Having seen (See e.g. Ref.18 and the references given there) how many different theories reproduce the well-known lepton-nucleus-collision data, and how many different versions of the ”generalized vector-meson model” fit the existing data for shadowing and/or anti-shadowing effects, it seems rather natural to ask: Wouldn’t it be useful also to have methods alternative to lepton-nucleus collision for this purpose?

IV. It is known that, in the usual parton description of  $F_2^p(x_B, Q^2)$ , the question whether photons dissociate has been bypassed by describing the reaction mechanism in a fast-moving frame — the appropriately chosen “infinite momentum frame” — in which the virtual photon carries little energy and thus the lifetime for the virtual hadronic state in the dissociation is short. But, as has already been pointed out more then twenty years ago by Nieh[1] the following is also true: Because of the shortened time scale for interaction in that frame, the dissociated hadronic state may not need to live very long to become effectively important; and hence, it seems there does not exist strong theoretical reason for making the assumption that the photon-dissociation mechanism is not important in the “infinite momentum” frame. Can we say: “ The question whether photon dissociation takes place is independent of the reference frame in which the observation is made”?

In this paper we propose to check hadronic dissociation of space-like photons by performing inclusive measurements in the fragmentation region of transversely polarized and unpolarized proton beams at HERA and by comparing the results with those obtained in corresponding hadron-hadron collisions. This is because we think, if we know what the characteristic features of hadron-hadron collisions are, we may check whether/when such typical features occur in the same manner in  $\gamma^*(Q^2)$ -hadron collision processes. By doing

so, we can find out experimentally whether/when  $\gamma^*(Q^2)$  behaves like a hadron. In other words, we can say whether/when hadronic dissociation of  $\gamma^*(Q^2)$  takes place. Hence, in this connection, it seems useful to know the following: Are there indeed such characteristic features for hadron-hadron collisions ? Is there experimental evidence that  $\gamma^*(Q^2)$  for some  $Q^2$ -values indeed behaves like a hadron ?

(a). A number of high-energy hadron-hadron collision experiments [21-25] — especially proton-proton collision experiments at CERN-ISR [21-24] show that the particles observed in the fragmentation regions play an extremely important role in understanding their production mechanisms. First of all, it is observed [21] that *limiting (i.e. energy-independent), rapidity-distributions exist in the rest frame of the fragmenting beam*. It is observed [22,23] in particular that, while  $\pi^+$ ,  $\pi^-$  and  $K^+$ -mesons with not too small transverse momenta ( $p_\perp \geq 0.5 \text{ GeV}/c$ , say) significantly contribute to the projectile fragmentation region (Feynman-x  $x_F \geq 0.4$ ), *the  $K^-$ -mesons do not*. Furthermore, it is observed [24-27] that hyperons, in particular  $\Lambda^0$ 's, produced in fixed target hadron-hadron and hadron-nucleus collisions are *polarized*, although neither the projectile nor the target is polarized. This polarization is *independent of the incident energy* and *it exists only in the fragmentation region of the projectile-proton!* The question whether such polarization phenomena also exists in lepton-lepton-collisions has also been discussed a long time ago (see Ref.28 and the references given therein). It is known in particular that the possible existence of  $\Lambda$ -polarization has been carefully searched in electron-positron collisions, and no evidence has been found [28].

(b). High-energy hadron-hadron collision experiments in which *the projectile-hadron is polarized transversely to the scattering plane* have been performed [29]. *Significant left-right-asymmetries (up to 40% ) with the following properties have been observed [29] in inclusive  $\pi^+$ ,  $\pi^-$ ,  $\pi^0$ ,  $\eta^0$  and  $\Lambda^0$  production processes* : First, *these asymmetries are  $x_F$ -dependent*: They are different from zero in the fragmentation region, and *only* in the fragmentation region ( $x_F \geq 0.4$ ) of the transversely polarized projectile-hadron. Second, *they are flavor-dependent*: The asymmetries for  $\pi^+$ ,  $\pi^-$  and  $\pi^0$  are very much different from one another.

Third, *they strongly depend on the quantum numbers of the projectile*: The observed asymmetries for proton and those for anti-proton are very much different from one another. Existence of such single-spin asymmetry effects in lepton-lepton or lepton-hadron collision processes is not known.

(c). High-energy photo- and electro-production experiments [18] with fixed proton-target and nuclear targets show that *real* ( $Q^2 = 0$ ) *and nearly real* ( $Q^2 \leq 1$  or  $2$   $GeV^2/c^2$ , say) photons *behave like vector mesons such as  $\rho^0, \omega, \phi, J/\psi$  etc* [4,2,10,11,17,18].

From the results mentioned in (a) and (b) we see that the projectile-proton in high-energy hadron-hadron and hadron-nucleus collisions exhibits striking features *in its fragmentation region*. These features (e.g. the  $\Lambda$ -polarization) observed *in the projectile fragmentation region* depends only on the quantum-numbers of the projectile, *but not on that of the hadronic target* (e.g. different nuclei). From the result mentioned in (c), we see that real ( $Q^2 = 0$ ) and space-like ( $Q^2 > 0$ ) photons indeed behave like hadrons for small  $Q^2$ -values. Having these experimental facts in mind, it seems natural to ask: Can we use the phenomena which have been observed — and only observed — in hadron-hadron collisions as characteristic features for hadron-hadron collision processes ? Shall we see *such characteristic features in proton's fragmentation region* in high-energy proton- $\gamma^*(Q^2)$  collisions if  $\gamma^*(Q^2)$  indeed behaves like a hadron? Can we use the observation of *such characteristic features in proton's fragmentation region* in proton- $\gamma^*(Q^2)$  collisions as signal for hadronic dissociation of  $\gamma^*(Q^2)$  for given values of  $Q^2$  ? It seems reasonable and useful to adopt the following standpoint: The phenomena which have been observed in hadron-hadron collisions and observed only in such collisions can be, and should be, considered as characteristic properties of hadron-hadron collision processes. In this sense, we propose to use the proton in  $\gamma^*(Q^2)$ -proton collisions as a “sensor” — as an “instrument” — to find out the following: Does the space-like photon  $\gamma^*(Q^2)$  with given virtuality  $Q^2$  act as a hadron ? It should be mentioned that, although the experimental facts listed in (a) and (b) can be understood in terms of a relativistic model (See Appendix and the references given there); but what we wish to find out here is merely whether/when  $\gamma^*(Q^2)$ -proton scattering show the same characteristic features as

those observed in hadron-proton scattering.

To be more precise, we propose to perform single-particle inclusive measurements in the fragmentation region of the transversely polarized proton  $p(\uparrow)$  and/or in that of the unpolarized protons  $p$  at DESY-HERA in the small- $x_B$  region for different  $Q^2$ -values, and to compare the obtained results with those obtained in the corresponding hadron-hadron collisions. We note: What we suggest to measure and to compare are *not* the absolute values of the cross sections but rather the  $\Lambda$ -polarization  $P_\Lambda$  or the left-right asymmetry  $A_N$  in  $\gamma^*(Q^2) + p$  processes. The quantities  $P_\Lambda$  and  $A_N$  are ratios of the difference and the sum of such cross sections. Hence, in these quantities, the  $1/Q^2$  factors due to the transverse geometrical size of  $\gamma^*(Q^2)$  are completely cancelled out.

In order to demonstrate in a quantitative manner how the  $Q^2$ -dependence of such dissociation processes may manifest itself, we examine the  $F_2^p(x_B, Q^2)$ -data [19,20] in the small- $x_B$  region. In Fig.1, we separate the well-known vector-dominance contribution (See e.g. 17,18 and the references cited there) from “the rest” which may be identified as “the part due to quark-antiquark continuum” or “the rest of the contributions due to the generalized vector-dominance model”, and we consider the following two extreme possibilities which correspond to two very much different physical pictures: (i) The hadronic dissociation of virtual space-like ( $Q^2 > 0$ ) photons take place for all possible  $Q^2$ -values. In particular, “the rest” mentioned above is independent of  $Q^2$ . In other words, in this picture  $\gamma^*(Q^2)$  should always be considered as a hadronic system — independent of  $Q^2$ . (ii) The hadronic dissociation of such photons depends very much on  $Q^2$ . In terms of a two-component picture (See e.g. Ref.8) the virtual photon  $\gamma^*(Q^2)$  is considered to be either in the “bare photon” state or in a hadronically dissociated state (“hadronic cloud”) described by the vector-dominance model [4,2,10,11,17,18 and the papers cited therein]. In other words, in this picture “the rest” mentioned above is strongly  $Q^2$ -dependent.

Let us first look at the left-right asymmetry data [29] for  $\pi^\pm$ -production in  $p(\uparrow) + p$  and see what we may obtain by replacing the unpolarized proton-target  $p$  by a photon with given  $Q^2$ ,  $\gamma^*(Q^2)$ . It is clear that the corresponding asymmetry which we denote by  $A_N(x_F, Q^2)$  will

have the following properties: If scenario (i) is correct, we shall see no change in  $A_N(x_F, Q^2)$  by varying  $Q^2$ . If scenario (ii) is true, there will be a significant  $Q^2$ -dependence. This is shown in Fig.2. Similar effects are expected also for  $K^+$ -mesons.

In this connection, it should also be mentioned that such studies can be performed, even when the detector is not able to differentiate between pions and kaons and/or to identify  $\Lambda^0$ 's. Due to the experimental fact that the left-right asymmetries  $A_N$  of  $\pi^+$  and  $\pi^-$  produced in the fragmentation region of transversely polarized protons have different signs, and the fact that the produced mesons are predominantly pions, (we recall that the forward protons can be identified by the leading proton spectrometer LPS at HERA), *a significant left-right asymmetry in electric charge is expected in the inclusive production processes  $p(\uparrow) + \gamma^*(Q^2) \rightarrow$  charged mesons +  $X$* , provided that the virtual photons  $\gamma^*(Q^2)$  dissociate hadronically.

We next consider the  $\Lambda$ -polarization  $P_\Lambda(x_F, Q^2)$  in the process  $p + \gamma^*(Q^2) \rightarrow \Lambda + X$  in which unpolarized proton beam is used. Also here, we expect to see *no  $Q^2$ -dependence for scenario (i) but a significant  $Q^2$ -dependence for scenario (ii)*. This is shown in Fig.3.

What do we expect to see in the fragmentation region of  $\gamma^*(Q^2)$  in the above-mentioned proton- $\gamma^*(Q^2)$  collision processes, when  $\gamma^*(Q^2)$  dissociates hadronically? In this connection, it is useful to recall that one of the most striking features of high-energy hadron-hadron collisions is the existence of limiting distributions for hadron-hadron-collisions as have been predicted in the late 1960's by Benecke, Chou, Yang and Yen [30]. Hence, if  $\gamma^*(Q^2)$  indeed behaves like a hadron, we expect to see that the momentum-distributions of the  $\gamma^*(Q^2)$ -fragmentation-products exhibit limiting behavior at sufficiently high energies. This can for example be done by varying the proton beam energy (820 GeV and 410 GeV, say) for fixed values of  $x_B$  and  $Q^2$ . Furthermore, we think it would be useful to perform the following measurements: First, identify the forward proton (e.g. with the leading proton spectrometer LPS at HERA), make sure that all the produced hadron have large-rapidity gaps with respect to this proton, and measure in the fragmentation region of  $\gamma^*(Q^2)$  the momentum-distributions of the hadrons at fixed  $x_B$  - and  $Q^2$ -values in order to see whether limiting distributions indeed exist. Next, identify the forwards going neutron (e.g. with the forward

neutron calorimeter FNC at HERA) which is well-separated by large rapidity gaps with respect to the produced hadrons, and measure the momentum-distributions of the  $\gamma^*(Q^2)$ -fragments to check if the hypothesis of limiting fragmentation HLF [30,31] is valid. After these have been done, compare the results with those obtained in lepton-proton scattering events without distinct large rapidity gaps (i.e. the “normal” events). The reasons for such measurements are not difficult to guess: Having in mind that single diffractive hadron-hadron scattering is nothing else but a special case of fragmentation processes for which HLF is valid [30], it is clear that such measurements and comparisons can/should be useful in clarifying the following questions: Do we see limiting fragmentation of space-like photons  $\gamma^*(Q^2)$  in the entire kinematical range of  $x_B$  and  $Q^2$ , or only in the small  $x_B$  and low  $Q^2$  region ? Is HLF valid only when “vacuum quantum numbers” are exchanged between the two colliding objects; or is it also valid when flavor(s) or color(s) are exchanged ?

The experiments proposed in this paper have been presented and discussed on various occasions in Berlin and Hamburg. The authors thank the organizers and participants of the seminars and workshop-sessions, especially M. Derrick, D.H.E. Groß, H. Haessler, H. Jung, S. Nurushev and R. Rittel for helpful discussions. This work was supported in part by Deutsche Forschungsgemeinschaft (DFG: Me 470/7-1).

## APPENDIX

The purpose of this appendix is to point out — from a theoretical point of view [30,31,34-40] — that the quoted[21-27] and the proposed experiments are closely related to one another, and that the proposed “sensor” is expected to work well.

We recall that, according to our present knowledge, baryons ( $p, \Lambda$  etc.) are made out of three valence quarks, vector- and scalar-mesons ( $\rho, \omega, \phi, \dots, \pi^\pm, K^\pm$  etc.) consist of a valence quark and a valence antiquark — together with in general a large number of sea quark and antiseaquark pairs. Universal distributions of all these quarks/antiquarks have been extracted from deep-inelastic lepton-hadron scattering and lepton-pair production experi-

ments. It is a remarkable fact that the CERN-ISR experiments[22,23,24] mentioned in (a) in the text show the following: The  $x_F$ -distributions for  $\pi^+(\equiv u\bar{d})$ ,  $\pi^-(\equiv d\bar{u})$  and  $K^+(\equiv u\bar{s})$  are very much the same as the distributions for the valence-quarks  $u(x_F)$ ,  $d(x_F)$  and  $u(x_F)$  respectively. The  $x_F$ -distribution for  $K^-(\equiv \bar{d}s)$ , however, behaves very much different from those of  $\pi^+$ ,  $\pi^-$  and  $K^+$ . In fact, it falls off extremely fast in the projectile fragmentation region  $x_F \geq 0.4$ ; and its magnitude is only about 1/20 of that for  $K^+$  at  $x_F \approx 0.6$  and 1/100 of that for  $K^+$  at  $x_F \approx 0.7$ . In other words,  $K^-(\equiv \bar{d}s)$  is almost absent in the fragmentation region of the proton  $p(\equiv uud)$ . Taken together with the empirical fact[21] concerning limiting fragmentation [30] these properties clearly show that *the valence quarks of the projectile hadron play a dominating role in meson-production in the projectile fragmentation region!*. To be more precise, it can be, and has been, explicitly shown [34,35] that, while the  $x_F$ -distribution for  $\pi^+$ ,  $\pi^-$  and  $K^+$  are the convolutions of the  $u_v$ ,  $d_v$  and  $u_v$  valence quarks with those of the corresponding antiseaquarks  $\bar{d}_s$ ,  $\bar{u}_s$  and  $\bar{s}_s$ , the  $x_F$ -distribution for  $K^-$  is that of the a sea quark  $s_s$  and an antiseaquark  $\bar{d}_s$ .

Next, we examine the data for the produced  $\pi^+$  and  $\pi^-$  in the single-spin reactions  $p(\uparrow) + p \rightarrow \pi^\pm + X$  mentioned in (b). It has been shown[36-38] that the observed left-right-asymmetry can be readily described in the framework of a relativistic quark-model in which the observed  $\pi^+$  and  $\pi^-$  are respectively the fusion-products of the valence quarks  $u_v$  and  $d_v$  of  $p(\uparrow)$  and antiseaquarks  $\bar{d}_s$  and  $\bar{u}_s$ . Here, the geometrical properties of the hadrons in particular the surface-effects play an important role. Furthermore, it has been shown[39] that the left-right asymmetry of  $\Lambda$ 's in  $p(\uparrow) + p \rightarrow \Lambda + X$  as well as the polarization in  $p + p \rightarrow \Lambda + X$  and  $p + \text{nucleus} \rightarrow \Lambda + X$  mentioned in (a) can also be understood [40] in terms of the above-mentioned relativistic quark model.

The CERN-ISR proton-proton collision experiment performed by Bellitini et al [21] explicitly show that the hypothesis of limiting fragmentation [30] hadron-hadron collisions is valid. This hypothesis is based on a geometrical picture (See Ref.30 and the papers cited there), in which the colliding hadrons at sufficiently high energies simply “go through each other”. During such collision processes, the colliding hadrons in general become excited, and

subsequently decay independently from each other. Single diffractive scattering, in which one of the colliding hadron remains unchanged, is nothing else but a special case. What do we know about the reaction mechanism(s) of limiting fragmentation of hadrons ? We know that, in such processes, only a rather limited amount of energy-momentum transfer takes place. But, the question whether /which other physical quantities (quantum numbers) can be or should be exchanged is yet unanswered. By performing the measurements proposed in this paper, we expect to see the following more clearly: (i) the relationship between hadron-hadron and virtual photon-hadron scattering; (ii) the relationship between large rapidity gap events[32,33] and normal events in lepton-proton scattering; and (iii) the mechanisms of color-, flavor- and vacuum quantum-number exchange in general, and the relationship between such quantum number-exchange and the validity of HLF [30,31] in particular.

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## Figures

Fig.1. Structure function  $F_2^p(x_B, Q^2)$  as a function of  $Q^2$ . The data-points are taken from [19,20]; and they are parametrized (shown as solid line) in order to carry out the quantitative calculation mentioned in the text. The dashed line is the contribution from the vector meson dominance. The difference, which is called “the rest”, is shown as dotted line.

Fig.2. Left-right asymmetry for pion-production in  $p(\uparrow) + \gamma^* \rightarrow \pi^\pm + X$  as a function of  $x_F$  at different values of  $Q^2$ . The data are for  $p(\uparrow) + p \rightarrow \pi^\pm + X$  and are taken from Ref. [29]. See text for more details.

Fig.3. Polarization for  $\Lambda$ -production in  $p + \gamma^* \rightarrow \Lambda + X$  as a function of  $x_F$  at different  $Q^2$ . The data are taken from Ref. [24-27]. See text for more details.





